# Transmission loss patterns from acoustic harassment and deterrent devices do not always follow geometrical spreading predictions

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**ABSTRACT**

Acoustic harassment and deterrent devices have become increasingly popular mitigation tools for negotiating the impacts of marine mammals on fisheries. The rationale for their variable effectiveness remains unexplained but high variability in the surrounding acoustic field may be relevant. In the present study, the sound fields of one acoustic harassment device and three acoustic deterrent devices were measured at three study sites along the Scandinavian coast. Superimposed onto an overall trend of decreasing sound exposure levels with increasing range were large local variations in sound level for all sources in each of the environments. This variability was likely caused by source directionality, inter-ping source level variation and multi-path interference. Rapid and unpredictable variations in the sound level as a function of range deviated from expectations derived from spherical and cylindrical spreading models and conflicted with the classic concept of concentric zones of increasing disturbance with decreasing range. Under such conditions, animals may encounter difficulties when trying to determine the direction to and location of a sound source, which may complicate or jeopardize avoidance responses.

**KEY WORDS**

acoustic harassment device (AHD); acoustic deterrent device (ADD); non-geometrical acoustic spreading; sound exposure level; multi-path interference; marine mammal-fisheries interactions; by-catch

## INTRODUCTION

Marine mammals interact with aquaculture and fisheries in a variety of ways. They can consume stocks or catch directly, inflict harm upon the catch and the fishing gear, introduce fecal coliform bacteria or parasites, and become severely or fatally caught in the gear (reviewed in Hammond and Fedak 1994, Dawson *et al.* 1998, Nash *et al.* 2000). These interactions should be limited both to protect the animals and to reduce the economic losses incurred by the fisheries. Acoustic approaches have been developed to alert the animals to the presence of gear or to encourage them to vacate an area (see Jefferson and Curry 1996 for a review). Repeated usage of an offensive stimulus, however, can lead to habituation, sensitization, attraction (once the sound has been associated with the presence of food) or, if loud enough, hearing damage. The use of gunshots, explosives, firecrackers and biological sounds have been largely ineffective in deterring marine mammals from fisheries, possibly for the reasons mentioned above (Shaughnessy and Semmelink 1981, Jefferson and Curry 1996).

Playback devices can be separated into two categories. Low level acoustic deterrent devices (ADDs, commonly referred to as “pingers”) are designed to displace animals temporarily from a region. On the other hand, high level acoustic harassment devices (AHDs, or “seal scarers”) are loud enough to cause pain and discourage predation (e.g., Milewski 2001). ADDs and AHDs differ in their output source levels (SLs) and frequency bands. ADDs typically operate in the 10- to 100-kHz band and emit SLs below 150 dB re 1 $\mu Pa^2 s$ @ 1 m, whereas AHDs operate mainly between 5 and 30 kHz at levels often exceeding 170 dB re 1 $\mu Pa^2 s$ @ 1 m (Northridge *et al.* 2006). (See Madsen 2005 for an explanation of level measurements and units.)

ADDs and AHDs are currently used to mediate many marine mammal-fisheries interactions worldwide. The playback of artificial sounds intended to mitigate conflicts between marine mammals and fisheries have met with mixed results. After introducing ADDs, several studies have documented actual changes in the behavior of harbor porpoises (*Phocoena phocoena*), one of the species most at risk of bycatch, leading to a reduction in entanglement (e.g., Kraus *et al.* 1997, Trippel *et al.* 1999) and in local abundance (Johnston 2002, Olesiuk *et al.* 2002). More than half of the New Zealand Hector's dolphins (*Cephalorhynchus hectori*) observed in one study avoided "white pinger" ADDs (manufactured by Dukane ®, $f_0$ = 9.6 kHz, pulse length = 400 ms) attached to gillnets (Stone *et al.* 2000). In a trial involving Lofi Tech AS AHDs in the Baltic Sea, depredation losses of salmon in traps due to gray seals (*Halichoerus grypus*) were halved, doubling the landed catch (Fjälling *et al.* 2006). Also, killer whales (*Orcinus orca*) were strongly displaced by Airmar AHDs in a study conducted in British Columbia (Morton and Symonds 2002). As a result of these kinds of findings, ADDs and AHDs have become increasingly popular for abating marine mammal interactions with fisheries (Johnston and Woodley 1998). Indeed, pingers are now mandatory in several types of gill-net fisheries around the world and have been suggested as a possible mitigation solution to by-catch associated with commercial trawling (de Haan *et al.* 1997, Reeves *et al.* 2001).

Not all experiments, however, have encountered this level of success. Cox *et al*. (2001) reported habituation of free-ranging harbor porpoises to one Dukane NetMark 100 pinger (10 kHz, 132 dB re 1µPa @ 1m). In another study, harbor porpoises partially habituated to both Airmar (10 kHz, 132 dB re 1$\mu Pa_{RMS}$@ 1 m) and SaveWave Black Save pingers (30–160 kHz, 155 dB re 1$\mu Pa_{RMS}$@ 1 m) over a 48-d course involving repeated activation and deactivation of these devices (Jørgensen 2006). Quick *et al.* (2004) reported survey results indicating that despite the elevated usage of AHDs, damage to Scottish marine salmon farms by harbor (*Phoca vitulina*) and gray seals increased between 1987 and 2001. Similarly, sea lions (*Otaria* *flavescens*) damaged catches in gillnets containing active pingers more often than those without pingers (Bordino *et al.* 2002). The bycatch levels of Franciscana dolphins (*Pontoporia blainvillei*), however, did fall in this same study when the pingers were active. The mechanisms leading cetaceans and pinnipeds to avoid or become attracted to fishing operations with functional ADDs and AHDs remain uncertain (Kraus 1999, Quick *et al.* 2004, but see Akamatsu *et al.* 1996, Kastak *et al.* 2005, Kastelein *et al.* 2006 for explorations of tolerance and habituation thresholds in seals and sea lions). This calls for research that examines how ADDs and AHDs actually function and transmit signals into the water. Quantifying the sound exposure level (SEL) of these devices will yield an improved understanding of the acoustic field to which animals are exposed when approaching a pinger underwater. Simple spherical and cylindrical spreading models and their associated zones of increasing impact with decreasing range (Richardson *et al.* 1995) may not be applicable for sound transmission in every instance (e.g., DeRuiter *et al.* 2006, Madsen *et al.* 2006). Although Terhune *et al*. (2002), for example, depicted that received levels varied greatly as a function of range for AHDs in the Bay of Fundy, Canada, the sound field of an ADD in the same area displayed less variability with range (e.g., Cox *et al.* 2001).

The nature of the sound field may be highly dependent on several factors including geographic location, habitat morphology, the time-frequency characteristics of the emitted signals, and the depth of source and receiver. Shallow water can lead to multipath propagation in which sound reflected off both the water's surface (including associated wave action) and the ocean bottom interferes constructively and destructively to create a complicated pattern of signal intensity as a function of range. This phenomenon may make it quite difficult to move away from a sound source by swimming down an intensity gradient in order to minimize exposure if the intensity gradient does not change predictably with distance. A detailed characterization of the sound fields of these devices is needed to understand their possible influence on marine mammal behavior.

In this study, we test whether typical ADD and AHD signals propagate according to the spherical or cylindrical spreading that is generally assumed when discussing zones of increasing impact (Richardson *et al.* 1995). We also explore the issue of variable SELs at close and distant ranges to several types of pingers and a single AHD in three shallow water environments in Sweden and Denmark.

## MATERIALS & METHODS

### A. Field sites

Three study sites were selected for the sound transmission experiments (Figure 1). The first was situated in a bay south of the island of Saltö, Sweden (referred to here as the "Saltö" field site, 58°51.7'N, 11°08.6'E). The bottom of the bay was relatively smooth, 13-20 m deep and was comprised of a mixture of mud and sand patches. Saltö was utilized on 5 June (SSs for Saltö, Sweden, summer) and 23, 24 and 29 September 2005 (SSf for Saltö, Sweden, fall). The second field site, used on 23, 24, and 29 September 2005, was located in another bay on the eastern side of the island of Sydkoster (referred to here as the "Kosterhamn" or KSf field site, 58°52.7'N, 11°05.4'E). The sandy seafloor graded smoothly from a depth of 12 m where the experiment was conducted to more than 20 m at the entrance of the deep fjord. The final site employed on 9 September 2005 was located in the shallow, sloping waters (5-15 m) of Jammerland Bay, Storebælt, Denmark (called "Jammerland" or JDf here, 55°36.0'N, 11°05.1'E) and was characterized by a hard, sandy bottom. These sites were representative of locations with respect to depth, topography, and bottom structure where pingers have been deployed by the fisheries. For all sites, sea state varied between 0 and 2 during recordings.

### B. Sound sources

Table 1 lists the specifications for the sound sources and Figure 2 provides the waveforms, spectra and spectrograms of the acoustic output of each device.

### C. Experimental protocol

There were a few differences in how the data were gathered and the setup of the recording chain between the field sites. Details of the equipment variability are listed in Table 2. The sound sources were deployed singly at a fixed depth either by suspending them from a buoy or the edge of a boat at the two Swedish sites. Measurements at Jammerland took place as part of a separate study on habituation of porpoises to pingers and employed a 5 x 3 array of 15 SaveWave pingers spaced 200 m apart and a 5 x 11 array of 55 Airmar pingers spaced 100 m apart. All pingers were attached approximately 0.5 m below the surface at the end of buoys measuring 2 m in length (fashioned from bamboo sticks lashed to a lead weight and a Styrofoam float). The two arrays were separated by about 5 km.

Recordings at all sites were made by towing a previously calibrated hydrophone from a small boat that drifted or was rowed very slowly past the sound source to cover both distant and close ranges. The Reson TC 4032 and BK 8101 hydrophones had cylindrical elements and became directional receivers at frequencies above 20 kHz. The Reson TC 4034 had a spherical element and was thus omni-directional at all frequencies. All hydrophones were calibrated in the laboratory before experiments commenced to ensure that sensitivities were in agreement with the standards given by the producers. For one set of experiments (SSs, JDf), the depth of the hydrophone was held constant at 2, 3 or 5 m. For the other experiments (SSf, KSf), a Star-Oddi CTD tag was attached 10 cm above the hydrophone element. This tag logged depth, salinity and temperature at 1 Hz and the data were downloaded at the end of each experiment. The sampling rates for all experiments ranged between 48 and 500 kHz depending on the recording system and the pinger that was being characterized. All data from the recording unit were stored on a laptop computer. Table 3 lists the recording duration and number of signals analyzed for each experiment. A handheld GPS was used at the Jammerland field site to provide the location of the sound sources. At the two other sites, a frequency shift keying (FSK)-modulated representation of GPS location was synchronously recorded to allow subsequent pairing of all received signals with their absolute locations (see Møhl *et al.* 2001).

The SL and directionality of the AHD were measured in a harbor near the field site prior to the field experiment. No boat activity was present at the time of this test. For the Airmar and Aquamark pingers, the measurements were made in an echo-free tank. The hydrophone was fixed 1 m from the transmitting element of the ADD or AHD and the entire setup was lowered to depth. To evaluate the directionality of the ADD or AHD, SL was calculated from several pings emitted at each of several orientations of the ADD or AHD relative to the hydrophone.

**D. Ping detection**

Using customized Matlab (Mathworks, Inc.) software, ping detection was partially automated by locating ping events in the recording that exceeded a user-defined amplitude threshold. To qualify for analysis, a ping needed to fulfill three criteria. It had to 1) be at least 10 dB louder than an interval of silence of the same duration immediately preceding the ping, 2) correspond to the durations listed in Table 1, and 3) be confirmed by the user. Signals from Jammerland were characterized by a poorer signal-to-noise ratio (SNR) resulting from the greater distances separating the pingers from the hydrophone. These signals were therefore identified manually by listening to the recordings and searching aurally for pings.

## E. Calculations

### *1. Range*

The latitude, longitude, and depth of each source and receiver were all converted into 3D meter space. At the Jammerland field site, the Cartesian distance between the receiver and the closest pinger source was computed as the range. For the two other sites, the Cartesian distance was simply calculated between the receiver and the single source.

### *2. Sound Exposure Level (SEL)*

All pings of constant frequency (see Table 1) were band-pass filtered around their central frequency using a two-pole Butterworth filter to exclude extraneous, non-ping energy. For frequency sweep signals, a two-pole Butterworth band-pass filter was applied above and below the lowest and highest frequencies contained within the signal. The received acoustic energy of every ping was computed as the energy flux density, or SEL, defined as the logarithm of the sum of the squared pressure over the ping duration in dB re 1 μPa$^2$s:

$$\mathrm{SEL} = 10\log\int_0^T p^2(t)dt + 120 = 10\log\left(\tfrac{1}{T}\int_0^T p^2(t)dt\right) + 10\log(T) + 120 \qquad (1)$$

where $p(t)$ is the instantaneous pressure at time $t$ and the duration $T$ of the signal contains 90% of the energy (Blackwell *et al.* 2004, Madsen 2005). A calibration signal of known sound level was routed through the entire recording chain and used as a reference for the computations.

The SaveWave signals contained energy beyond the range of the flat frequency response of the hydrophone. To compensate for this reduced sensitivity, these signals were adjusted by amplifying the high frequencies in this range. At the greatest distances where the SNR was poor, the SELs from the SaveWave were calculated once the energy of the background noise immediately preceding the signal was subtracted. Airmar recordings from Jammerland were similarly characterized by a poor SNR at large distances. These ping levels were therefore determined by the peak of the average power spectrum calculated over the complete signal duration.

## RESULTS

Figure 3 displays the SL measurements of the Airmar and Aquamark in different directions, revealing anomalies of up to 4.7 and 25.7 dB, respectively. Figure 4 plots SEL as a function of range for all sound sources in each environment. The lines indicating spherical and cylindrical spreading are not intended to compare the expected and actual SELs but rather to show patterns of the slope predicted by these basic models. Figure 4 illustrates that despite an overall trend for SEL to decrease with increasing distance, a tremendous amount of dynamic range in the SEL existed over a given range. This phenomenon appeared consistently in the plots for all of the sound sources and environments.

The upper left subpanel of Figure 4 is enlarged in Figure 5 to show that fluctuations in SEL at a particular range were often much greater than those between two rather different ranges. Figure 5 can also be viewed as the series of SELs that an animal would encounter if it were traveling directly towards or away from the AHD Lofitech source. An animal traveling away from the AHD would experience a constantly fluctuating SEL, generally trending downwards, but with successive pings in the sequence increasing and decreasing unpredictably.

## DISCUSSION

There was a pronounced variability in SELs of up to 19 dB at constant ranges out to beyond 1 km from the AHD (Lofitech). For the ADDs (*i.e.*, the Airmar, Aquamark and SaveWave pingers), the variability was less pronounced at long ranges. At a range of 100 m, there was up to 10 dB of variation for the Airmar pinger and up to 6 dB for the Aquamark 100 (Figure 4). The overall trend of decreasing SEL with increasing range from the ADD or AHD (Figures 4 & 5) was disrupted by interference patterns. Such variability and deviation from spherical or cylindrical spreading expectations, even at large distances from the source, conflicts with the classic description of concentric zones of increasing disturbance with decreasing range (Richardson *et al.* 1995). This also poses a difficulty for an animal attempting to predict level on a fine scale and orient with respect to this variable intensity gradient. The spatial extent of these zones is clearly difficult to predict, especially given the plasticity of an animal's thresholds of detection, injury and avoidance resulting from its motivation, behavior and physiological state.

One of the motivating concerns for launching this study was the possibility that constructive interference could generate unpredictable pinger SEL hotspots of sufficiently high intensity that might lead to unexpected hearing damage in marine mammals. Although the recorded levels fell below the intensities that caused temporary threshold shifts and temporary losses of hearing sensitivity (i.e., 195 dB re 1$\mu Pa^2 s$, Finneran *et al.* 2005), Figures 4 and 5 reveal that moving away from the source did not necessarily guarantee that SEL would decrease. This alters the way in which we should understand an animal's perception of an AHD- or pinger-emitted sound field. While swimming away from a sound source, the animal could be exposed to dramatic sound level variations over very small spatial scales. Theoretically, the sound level may shift by several orders of magnitude within a fraction of a meter (Wahlberg 2006). If the animal integrates time of arrival and phase shift differences between its ears with a series of level cues and these two sets of sensory cues oppose one another, it may be difficult to determine the direction to and location of the sound source. Natural orientation cues may also be obscured by artificial signals through masking and from temporary threshold shifts reported to occur at levels below those measured here (Schlundt *et al.* 2000). This possibility conflicts with the hypothesis that animals learn to avoid an area due to an acoustic deterrent. The rapid and unpredictable variations in the sound intensity as a function of range to the pinger may seriously confuse the animal and make avoidance responses more complicated than intended. If the animal uses subsequent pings to improve its ability to assess directionality of a signal (as indicated by Kastelein *et al.* 2007), this problem becomes more serious.

We still need to test whether large spatial variations in SELs prevent animals from reacting appropriately to ADD and AHD signals. Besides the actual problem of detection and determination of the direction to the sound source, the behavior of the animals may be influenced by a learning component that needs to be addressed. Grey seals lifted their heads out of the water in response to AHD signals (Bordino *et al.* 2002, Fjälling *et al.* 2006) and physiological (Clark 1991), behavioral (Olesiuk *et al.* 2002) and masking (Southall *et al.* 2000) effects have been observed. Further studies between acoustic deterrents and marine mammal responses are required to examine how animals behave around and react to fishing nets with and without pingers. These issues could be addressed by comparing the acoustic measurements of the pinger signals reported here with the behavior of animals swimming through the sound field.

The variability in the SEL may be an important factor to consider when evaluating the implementation of acoustic mitigation devices in fishery regimes. The dynamic characteristics of a trawl, for example, could influence the source directionality and multipath interference, potentially contributing to even larger SEL fluctuations than observed under static conditions. Some newly developed acoustic mitigation devices (*i.e.*, DDD02F) operate with SLs higher than 160 dB re 1 μPa$^2$s, further contributing to concerns surrounding their implementation (Dalgaard Balle and Larsen, unpublished data).

The variability in SELs observed in this study could have been caused by a combination of interping SL variations, bathymetry, wave action influencing the surface reflections, multipath interference, and source directionality. Salinity and temperature effects were unlikely to have played a strong role because neither a pronounced halocline nor thermocline was observed (measured at SSf and KSf with the Star-Oddi CTD tag) and because computer modeling has demonstrated that such an influence would be rather small for the ranges of interest here (Westerberg and Spiesberger 2002). The pingers were mounted vertically to record signals from the broadside axis, thereby minimizing directionality effects. The Airmar pinger showed sub-dB variations in its inter-ping SL when recorded in a fixed direction, whereas the Aquamark 100 showed a larger variation, possibly because of slight variations in SL for the various sound types emitted (Figure 3). The broadside SL of the Airmar pinger varied less than 2 dB when rotating the pinger about its axis (Figure 3). Therefore, because the Airmar pingers were recorded at small angles relative to their axis of symmetry, most of the variability in their SELs as a function of range was attributed to multipath propagation. Multipath modeling demonstrates that variability of the magnitude observed here can result from the interference of direct, surface-reflected and bottom-reflected rays (Wahlberg 2006).

For the Aquamark pinger, the transmission beam pattern was more complicated and variable and depended on which of the two types of signals was being emitted (Figure 3). The

SL was not only variable between the pinger's axis of symmetry and broadside, but also varied by 13 dB on the broadside when rotated about its axis of symmetry. It was not clear to what extent the source directionality and multipath variation each contributed to the SEL variation for the Aquamark pinger. The signals produced by the SaveWave pingers were variable in duration and frequency spectrum, causing the transmitted energy to vary from one signal to the next, which may at least partially explain the observed SEL variability.

The soft and hard bottom locations did not produce clear differences in the SEL variability. This is surprising since a softer bottom should have rendered fewer multipaths, leading to a less complicated SEL pattern as a function of range. The soft bottom may have reflected sound better than expected, diminishing the differences in acoustic propagation between the experimental sites. In addition, the soft bottom site was shallower than the hard bottom site, which may have confounded the possible effects of bottom properties on multipath propagation.

The efficiency of pingers, quantified both in terms of their power demands and the quantity of sound that they are able to discharge, may be improved by decreasing the duration of the emitted signal, which would lead to a reduction in the interference patterns measured here. This suggestion must be balanced, however, with the important issue that to obtain a maximum effect, the signal loudness should exceed some critical threshold for an animal's particular integration time that will produce the desired avoidance or disturbance response. More work is required to explore the behavior of seals and porpoises in relation to ADD and AHD sound sources with realistic SELs and their interaction with fishing gear in light of more complex, non-geometrical spreading models. The interplay between conservation and marine mammal and fishery interactions must continue to be engaged by consistent research efforts that explore the ways in which these ADDs and AHDs actually operate and influence the animals that they are intended to target.

In conclusion, we found that signals from ADDs and AHDs did not propagate in a coastal environment according to the simple models of spherical or cylindrical spreading that posit zones of increasing impact with decreasing range (Richardson *et al.* 1995). The acoustic field to which animals are exposed when approaching a pinger underwater is thus complicated and not easily described by these concentric zones of responsiveness, masking and discomfort relative to the range from the ADD/AHD. Instead, the SEL varied several-fold within very short distances, likely as a result of the interference of direct, surface-reflected and bottom-reflected rays (Wahlberg 2006). The behavior of seals and cetaceans in relation to the sound field of ADDs and AHDs should be prioritized in future research.

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**TABLES**

Table 1. Specifications of sound sources described in this study.

| Sound source | Manufac-turer | Field site[a] | Approximate source level (dB re 1 µPa RMS @ 1 m) | Frequen-cy (kHz) | Signal type[b] | Average duration (ms) |
|---|---|---|---|---|---|---|
| ADD | Airmar | SSf, KSf | 132 | 9.8 | C | 300 |
| ADD | Airmar | JDf | 132 | 10 | C | 300 |
| ADD | Aquamark | SSf, KSf | 145 | 20-160 | C, S | 300 |
| ADD | SaveWave | JDf | 155 | 30-120 | S[c] | 200-425 |
| AHD | Lofitech | SSs, KSf | 193 | 15.6 | C | 200 |

[a] SSs: Saltö, Sweden, spring

KSf: Kosterhamn, Sweden, fall

SSf: Saltö, Sweden, fall

JDf: Jammerland, Denmark, fall

[b] C: constant frequency

S: frequency sweep

[c] The SaveWave pinger produced a series of upward-modulated frequency sweeps, which were of variable duration and rich in harmonics. The SLs of these signals were similar. Sweeps were repeated up to 4 times per signal. Signals were repeated with a variable interval of up to several tens of seconds. All parameters changed randomly from one signal to the next.

Table 2. Equipment used at each field site with corresponding amplification and filtering details. Abbreviations: B&K = Brüel and Kjær (Danish hydrophone company), DAT = Digital Audio Tape Recorder, HP = high pass filter; LP = low pass filter, DAB=Data Acquisition Board. SSs: Saltö, Sweden, spring, KSf: Kosterhamn, Sweden, fall, SSf: Saltö, Sweden, fall, JDf: Jammerland, Denmark, fall. All hydrophones were calibrated in the laboratory before fieldwork.

| **Field site** | **Hydrophone** | **Recording unit** | **Sound source** |
|---|---|---|---|
| SSs | BK 8101 | DAT | AHD |
| SSf | Reson TC 4032 | DAB | Airmar |
| | Reson TC 4034 | | Aquamark |
| KSf | Reson TC 4032 | | Airmar |
| | Reson TC 4034 | | AHD, Aquamark |
| JDf | Reson TC 4032 | DAB | SaveWave, Airmar |

Table 3. Recording duration and number of signals analyzed for each sound source and field site. See Table 1 for abbreviations.

| Sound source | Field site | Recording duration (min) | Number of signals measured |
|---|---|---|---|
| Lofitech AHD | KSf | 54 | 388 |
| | SSs | 93 | 538 |
| Airmar ADD | SSf | 41 | 423 |
| | KSf | 62 | 211 |
| | JDf | 12 | 35 |
| Aquamark ADD | SSf | 41 | 58 |
| | KSf | 62 | 50 |
| SaveWave ADD | JDf | 11 | 40 |

## FIGURE CAPTIONS

Figure 1. Maps of study locations.

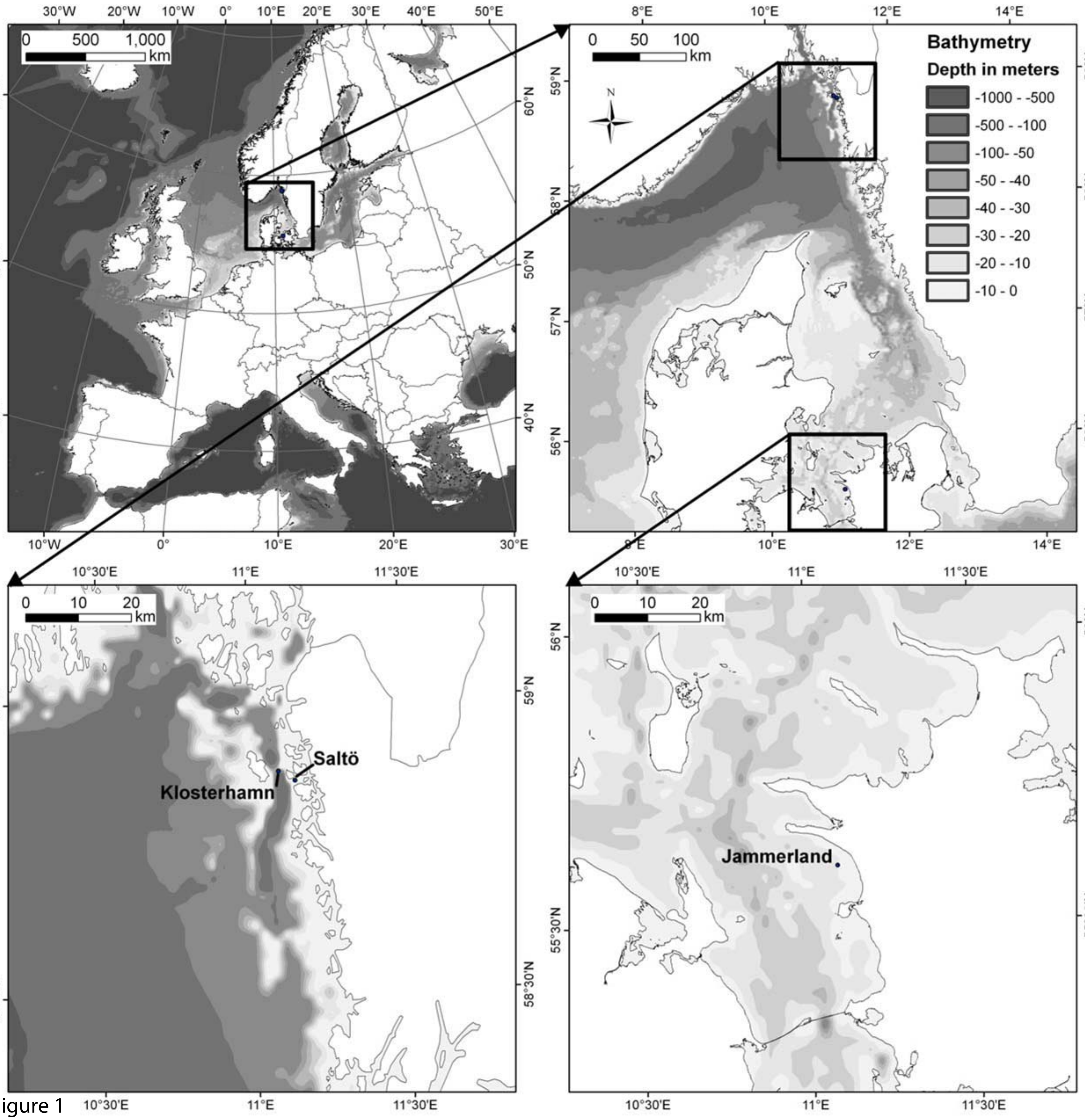
Figure 2. Waveforms (left), spectra (center) and spectrograms (right) for each of the sound sources. The SaveWave signal was an example taken from the larger repertoire of signals (see Table 1) in which sweep duration, start and end frequencies, and number of repetitions changed randomly.

Figure 3. A) Source level (at 1 m distance) of the Airmar and Aquamark pingers recorded in various directions. The levels of the CF (constant frequency) and sweep ping are denoted uniquely (+ and ○, respectively). B) The orientation scenarios 1-6 of the pingers and receivers are illustrated graphically beneath the plots. The pinger (black and white oval) was recorded from the direction indicated by the origin of the arrow. The first pinger was recorded from its north pole, the middle four from the equator at four different pinger orientations and the final image from the south pole.

Figure 4. Received sound exposure level as a function of range. Slopes obeying cylindrical and spherical spreading laws and absorption are shown by the dotted and solid lines, respectively.

Figure 5. Received sound exposure level from a Lofitech AHD source as a function of range for a recording using a hydrophone that continuously approached a stationary pinger. Imagining an animal moving along a track line similar to the one here, a steadily reliable decrease with

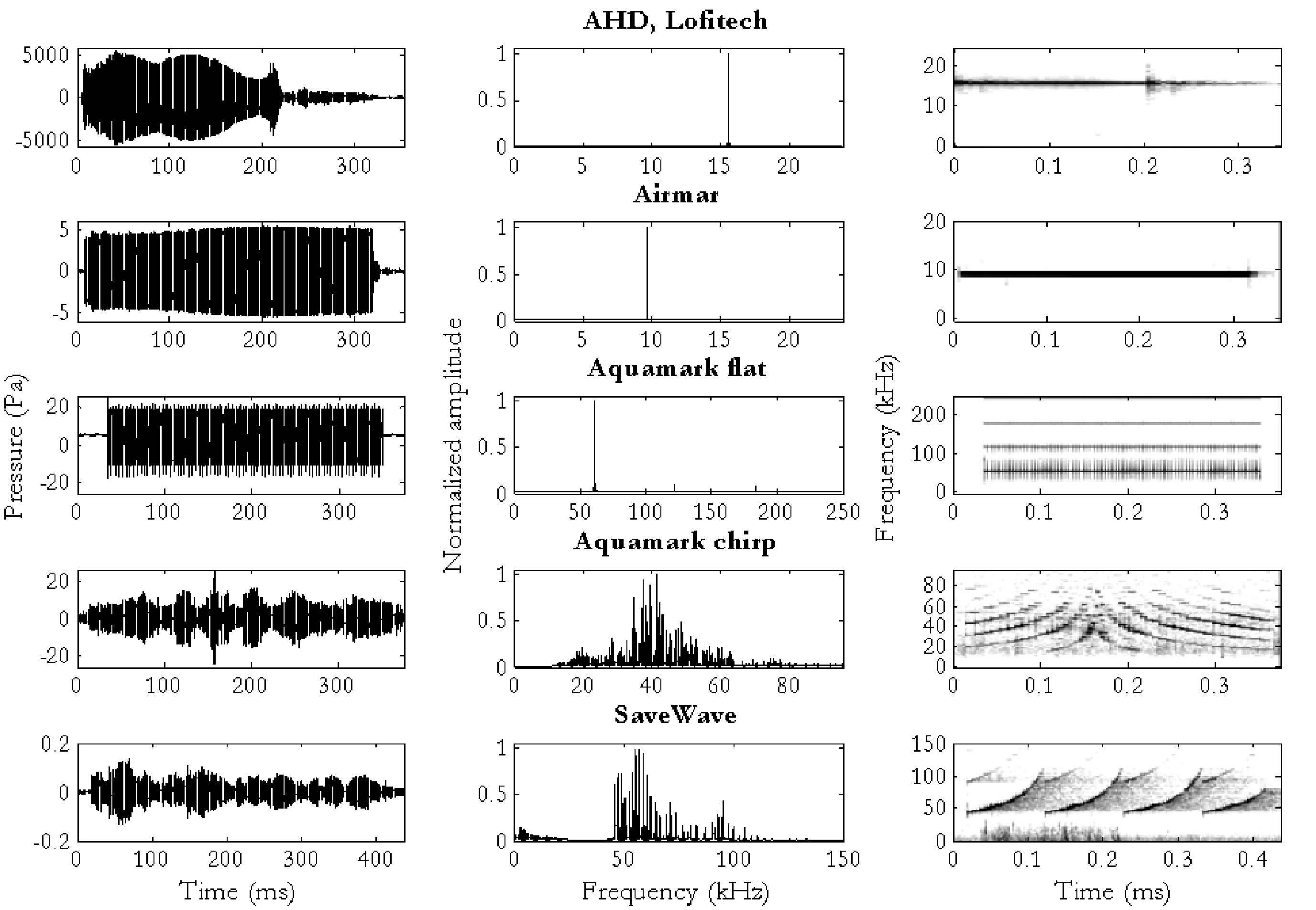
increasing range would not occur since the levels fluctuate dramatically. See text for further elaboration.



Bathymetry
Depth in meters
-1000 - -500
-500 - -100
-100- -50
-50 - -40
-40 - -30
-30 - -20
-20 - -10
-10 - 0
Saltö
Klosterhamn
Jammerland


Figure 1

Figure 2



AHD, Lofitech
Airmar
Aquamark flat
Aquamark chirp
SaveWave
Pressure (Pa)
Normalized amplitude
Frequency (kHz)
Time (ms)
Frequency (kHz)
Time (ms)

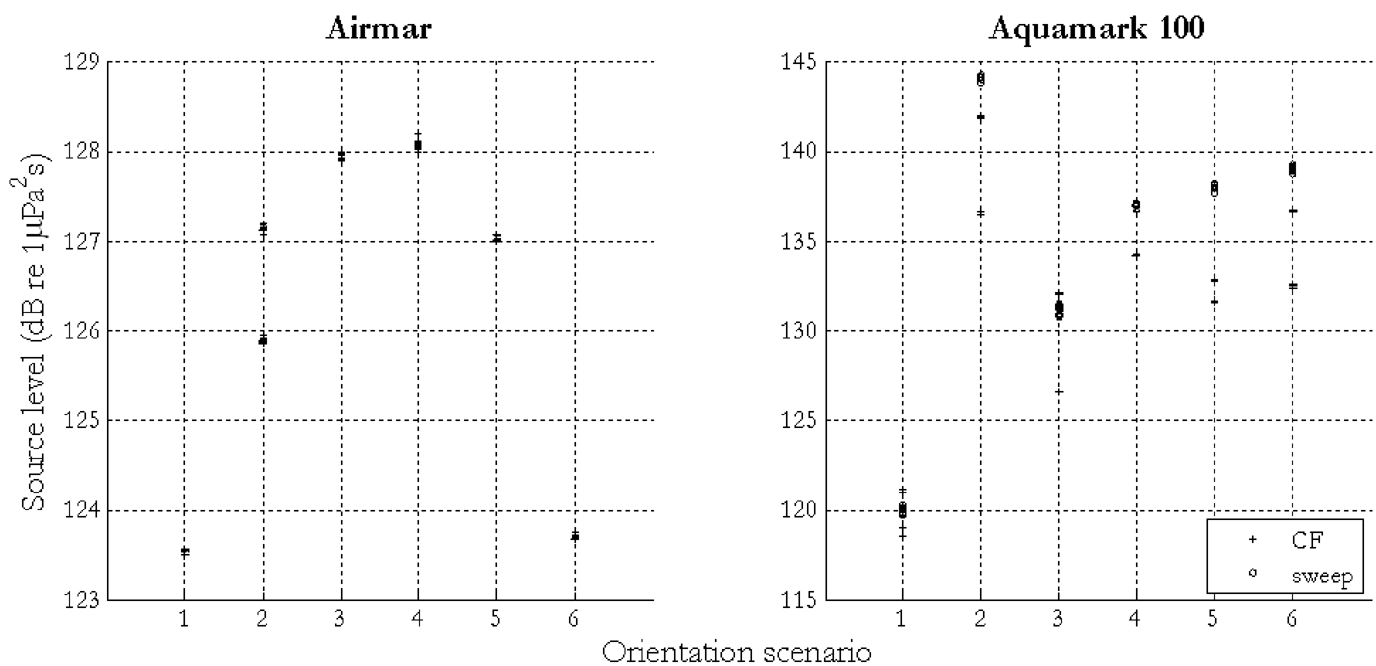

Airmar
Aquamark 100
Source level (dB re 1μPa²s)
Orientation scenario
CF
sweep
129
128
127
126
125
124
123
145
140
135
130
125
120
115
1
2
3
4
5
6

Figure 3A

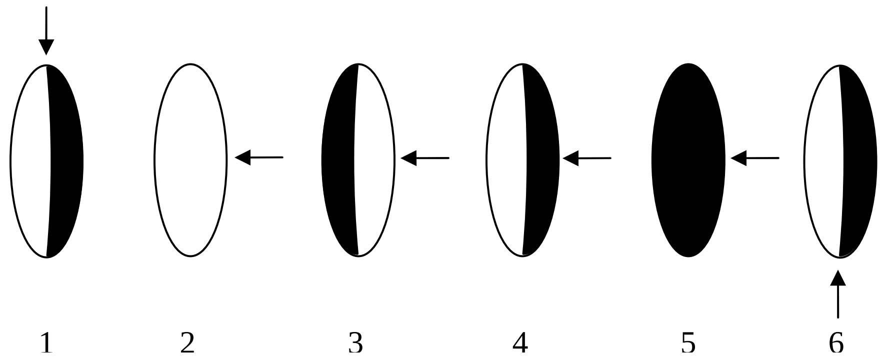
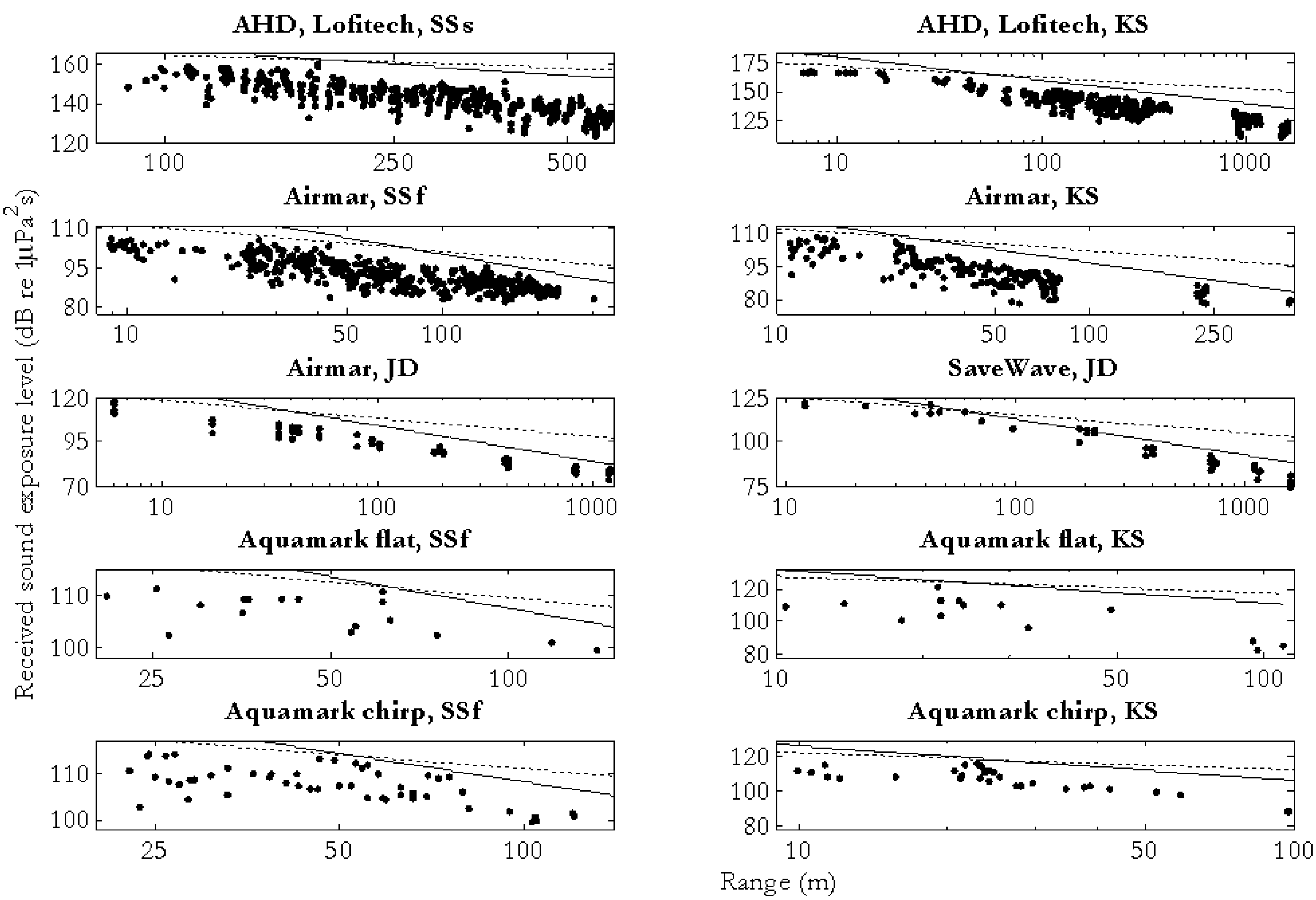
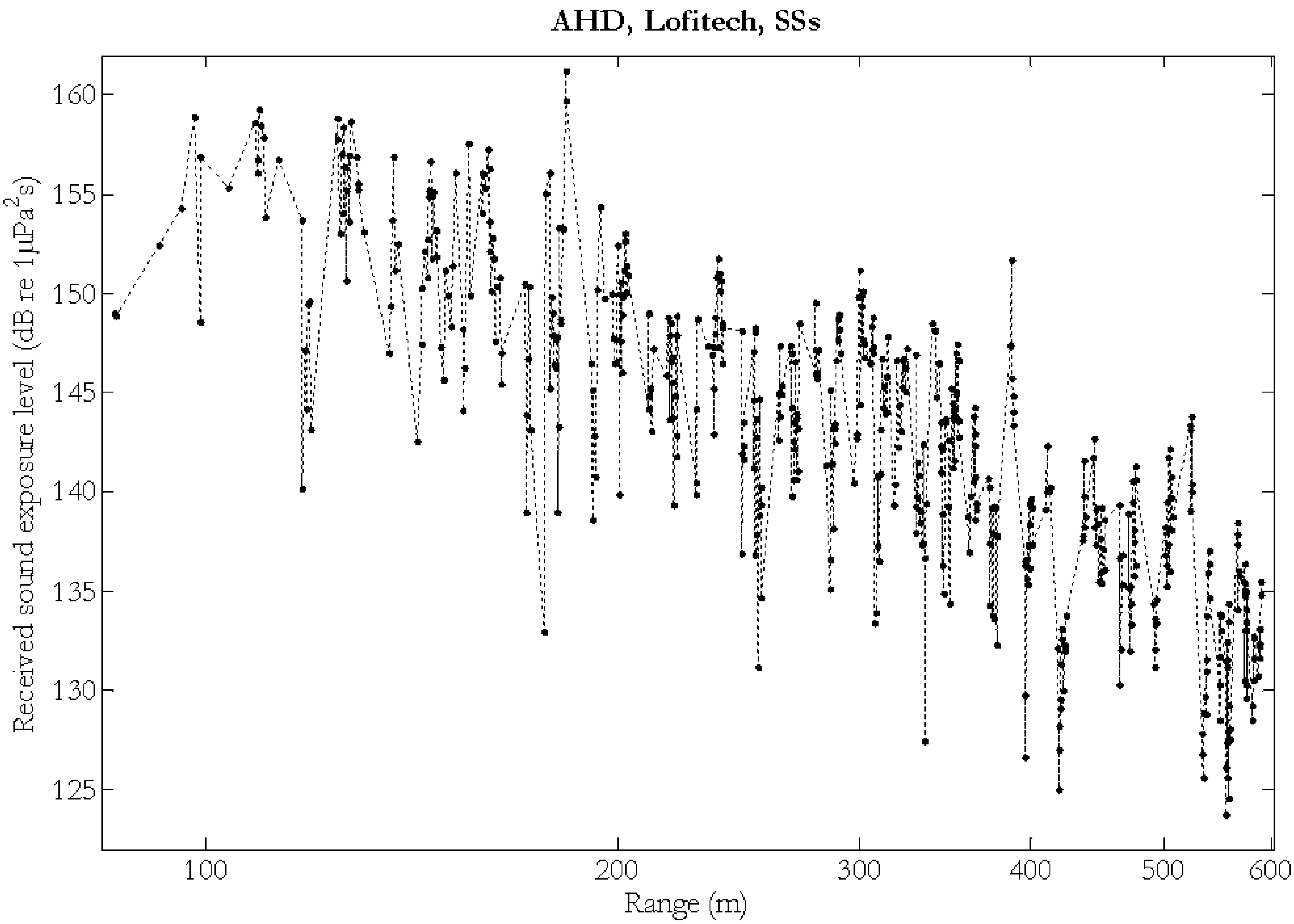



Figure 3B



AHD, Lofitech, SSs
AHD, Lofitech, KS
Airmar, SSf
Airmar, KS
Airmar, JD
SaveWave, JD
Aquamark flat, SSf
Aquamark flat, KS
Aquamark chirp, SSf
Aquamark chirp, KS
Received sound exposure level (dB re 1μPa$^2$s)
Range (m)


Figure 4



AHD, Lofitech, SSs
Received sound exposure level (dB re 1μPa²s)
160
155
150
145
140
135
130
125
100
200
300
400
500
600
Range (m)


Figure 5